Energy Barrier and Magnetic Properties of Exchange-Coupled Hard-Soft Bilayer System

Z. S. Shan, J. P. Liu, Vamsi M. Chakka, H. Zeng, J. S. Jiang

***Abstract*—In this paper the magnetic properties of an exchange-coupled hard-soft bilayer system have been analyzed based on its energy-barrier characteristics. Analytical solutions of the magnetic and structural parameters such as the energy barriers, the coercivities, the critical coupling-constant, the critical coupling dimension of soft phase, and the energy product have been derived. These analytical solutions reveal the correlation between the magnetic properties and the physical dimensions of its soft and hard phase constituents.**

***Index Terms*--Energy barrier, energy product, exchange coupling, hard phase, soft phase, spring magnet.**

I. Introduction

Exchange-coupled nanocomposite magnets have the potential of very high energy products $(BH)_{max}$, because they may take advantage of the high magnetization of the soft magnetic constituent and the high coercivity of the hard magnetic constituent [1], [2]. Many modeling analyses have been done on this new type of composite magnetic materials [2]-[4]. In this modeling analysis in this paper, the optimized structural and magnetic properties of the two-phase system, viz., the potential energy product $(BH)_{max}$, the critical values of the coupling constant and the coercivity, and the critical dimension of the soft phase constituent, have been derived.

In this paper, a simple bilayer model has been established based on the Stoner-Wohlfarth model [5]. A simple exchange-coupled soft and hard bilayer possesses the main feature of a spring magnet. Analytical solutions, which indicate the correlation between the magnetic and structural properties of the bilayer system have been derived. These solutions are useful for understanding the structural and magnetic properties of exchange-coupled nanocomposite magnets.

II. Energy Equation and Energy Barrier

The energy of an exchange-coupled soft and hard bilayer can be expressed as

$$E(\alpha,\beta) = E_S(\alpha) + E_H(\beta) + E_{exchange}(\alpha,\beta) \tag{1}$$

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J. P. Liu, Vamsi M. Chakka, and H. Zeng are with Institute for Micromanufacturing, Louisiana Tech University, Ruston, LA 71272. (email: pliu@coes.latech.edu, c_vamsi@hotmail.com).

Z. S. Shan is with Komag Inc. 1710 Automation Parkway, San Jose, CA 95139. (email: zsshan1@yahoo.com).

H. Zeng is also with IBM T.J. Watson Research Center, NY 10598.

J. S. Jiang is with Argonne National Laboratory, Argonne, IL 60439.

where the $E_S(\alpha)$, $E_H(\beta)$, and $E_{exchange}(\alpha,\beta)$ are the energy of the soft and hard phases and the coupling energy between them. They can be written as

$$E_S(\alpha) = -HM_St_S\cos(\theta-\alpha) + K_St_S\sin^2\alpha \tag{2}$$

$$E_H(\beta) = -HM_Ht_H\cos(\theta-\beta) + K_Ht_H\sin^2\beta \tag{3}$$

$$E_{exchange}(\alpha,\beta) = -J\cos(\beta-\alpha) \tag{4}$$

where H, M, K, and t are the applied external field, the magnetization, the anisotropy constant, and the thickness of the soft or hard phase constituent. The subscripts S and H denote the soft and hard phases. α, β, and θ are the angles of the M_S, M_H, and H with respect to the easy axis (Fig. 1). J is the coupling constant between soft and hard phases.

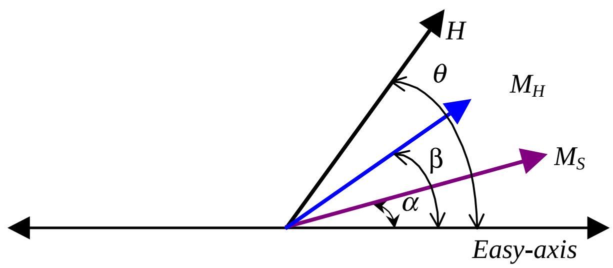

Fig. 1. Schematic configuration of M_S, M_H, and H field with respect to the energy easy axis.

The energy-barrier $E_{B\text{-}S}$ for the soft phase (or $E_{B\text{-}H}$ for hard phase) can be determined as

$$E_{B-S} = E_{S-Max} - E_{S-Min} \text{ or } E_{B-H} = E_{H-Max} - E_{H-Min} \tag{5}$$

where the subscripts *Max* and *Min* represent the maximum and minimum energy. The angle values of α and β have to be predetermined while calculating the energy-barriers $E_{B\text{-}S}$ and $E_{B\text{-}H}$. The theoretical analysis [6] and the experimental work [7], [8] confirmed that both M_S of the soft-phase and M_H of the hard-phase are aligned with H for large H-values (i.e., $\alpha = \beta = \theta = 0°$). When the H field is reversed and its magnitude is increased (θ=180° and H>0), M_S reverses at the coercivity of soft phase $H_{C\text{-}S}$, and then M_H reverses at the coercivity of hard phase $H_{C\text{-}H}$ (Fig. 2).

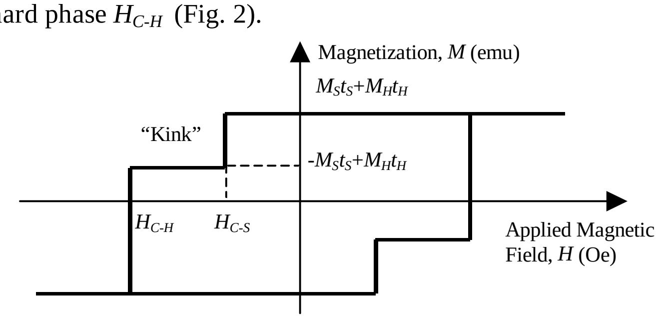

Fig. 2. Hysteresis loop for a hard-soft composite magnet.

Therefore, the angle values are θ = 180°, α = β = 0° for $H_{C\text{-}S} > H > 0$ while determining $E_{B\text{-}S}$, and $\theta = \alpha$ = 180°, β = 0° for $H_{C\text{-}S} < H < H_{C\text{-}H}$ while determining $E_{B\text{-}H}$ [9].

The analytical solutions of $E_{S\text{-}Max}$, $E_{S\text{-}Min}$, $E_{H\text{-}Max}$ and $E_{H\text{-}Min}$ can be determined by

$$\frac{\partial E}{\partial \alpha}=0 \quad \text{and} \quad \frac{\partial^2 E}{\partial \alpha^2}<0 \quad \text{for } E_{(B-S)Max} \tag{6}$$

$$\frac{\partial E}{\partial \alpha}=0 \quad \text{and} \quad \frac{\partial^2 E}{\partial \alpha^2}>0 \quad \text{for } E_{(B-S)Min} \tag{7}$$

$$\frac{\partial E}{\partial \beta}=0 \quad \text{and} \quad \frac{\partial^2 E}{\partial \beta^2}<0 \quad \text{for } E_{(B-H)Max} \tag{8}$$

$$\frac{\partial E}{\partial \beta}=0 \quad \text{and} \quad \frac{\partial^2 E}{\partial \beta^2}>0 \quad \text{for } E_{(B-H)Min} \tag{9}$$

The derivations of $E_{B\text{-}S}$ and $E_{B\text{-}H}$ are similar to what has been done in [6], and here we write down (10) and (11) directly to save the space:

$$E_{B-S}=K_S t_S\left(1-\frac{H-J/M_S t_S}{H_{K-S}}\right)^2 \tag{10}$$

$$\left(\text{where } H_{K-S}=2K_S/M_S;\ \theta=180^\circ,\ H_{C-S}>H\right)$$

$$E_{B-H}=K_H t_H\left(1-\frac{H+J/M_H t_H}{H_{K-H}}\right)^2 \tag{11}$$

$$\left(\text{where } H_{K-H}=2K_H/M_H;\theta=180^\circ,H_{C-H}>H>H_{C-S}\right)$$

From the physical point of view, the energy barrier is the key issue in controlling the moment reversal properties of a spring magnet. Equations (10) and (11) indicate the correlation between the energy barriers and the magnetic and structural parameters of the hard-soft composite magnets, which is valuable for the optimal design of ~~a~~ spring magnet.

III. Magnetic Properties Of Bilayer System

A. Energy Barrier Height

Fig. 3 shows the normalized curves of ($E_{B\text{-}S}$) vs. $(J/M_S t_S)/H_{K\text{-}S}$ for soft phase and ($E_{B\text{-}H}$) vs. $(J/M_H t_H)/H_{K\text{-}H}$ for hard phase while H=0.

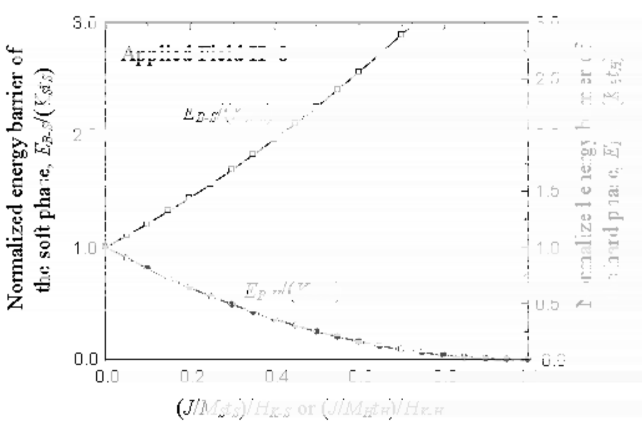

Fig. 3. Effects of $(J/M_S t_S)/H_{K\text{-}S}$ on normalized energy barrier $E_{B\text{-}S}/K_S t_S$ and $(J/M_H t_H)/H_{K\text{-}H}$ on normalized energy barrier $E_{B\text{-}H}/K_H t_H$.

Energy barrier $E_{B\text{-}S}/(K_S t_S)$ of soft phase increases and the energy barrier $E_{B\text{-}H}/(K_H t_H)$ of hard phase decreases with the coupling constant J. This is the physical origin because of which, exchange-coupled composite magnet may take the advantages of the high coercivity from the hard phase and high magnetization from soft phase. This will be discussed in more detail in the next two sections.

B. Coercivity

The energy barrier $E_{B\text{-}S}$ or $E_{B\text{-}H}$ decreases with increasing applied field in the direction θ=180°. The applied magnetic field H that makes the energy barrier $E_{B\text{-}S}$ or $E_{B\text{-}H}$ vanish is the coercivity, i.e., the coercivities of the soft phase and the hard phase, $H_{C\text{-}S}$ and $H_{C\text{-}H}$, can be determined from the following conditions:

$$\left(1-\frac{H_{C-S}-J/M_S t_S}{H_{K-S}}\right)=0 \text{ and } \left(1-\frac{H_{C-H}+J/M_H t_H}{H_{K-H}}\right)=0$$

Therefore H_{C-S} and H_{C-H} can be obtained as :

$$H_{C-S}=H_{K-S}+\frac{J}{M_S t_S}=\frac{2K_S}{M_S}+\frac{J}{M_S t_S}=\frac{2K_S}{M_S}\left(1+\frac{J}{2K_S t_S}\right) \tag{12}$$

$$H_{C-H}=H_{K-H}-\frac{J}{M_H t_H}=\frac{2K_H}{M_H}-\frac{J}{M_H t_H}=\frac{2K_H}{M_H}\left(1-\frac{J}{2K_H t_H}\right) \tag{13}$$

Equations (12) and (13) indicate that $H_{C\text{-}S}$ increases by $J/M_S t_S$ in magnitude or by $J/2K_S t_S$ in percentage, and $H_{C\text{-}H}$ decreases by $J/M_H t_H$ in magnitude or by $J/2K_H t_H$ in percentage. The correlation between the coercivities and the magnetic properties and thickness of soft and hard phases indicates the possible way of controlling or adjusting the values of $H_{C\text{-}S}$ and $H_{C\text{-}H}$. Since $J/2K_S t_S > J/2K_H t_H$ for most conventional hard-soft composite magnets, the coercivity increase in soft phase is greater than the coercivity decrease in hard phase, and this is desirable for the ideal spring magnets.

C. Critical Parameters $H_{Critical}$, $J_{Critical}$, $t_{S\text{-}Critical}$

It is interesting to find out that the difference ($H_{C\text{-}H}$ - $H_{C\text{-}S}$) (see Fig. 2 and (12) and (13)) can be adjusted by changing the magnetic parameters and thickness of the soft and hard phases. This difference, or the loop kink as shown in Fig. 2, will vanish if the following conditions are satisfied:

$$H_{C-H} - H_{C-S} = \\ =\left(H_{K-H}-\frac{J}{M_H t_H}\right)-\left(H_{K-S}+\frac{J}{M_S t_S}\right)=0 \tag{14}$$

Equation (14) can be fulfilled by increasing J to $J_{Critical}$, while keeping other film parameters constant

$$i.e.\ \left(H_{K-H}-\frac{J_{Critical}}{M_H t_H}\right)-\left(H_{K-S}+\frac{J_{Critical}}{M_S t_S}\right)=0$$

Therefore,

$$J_{Critical}=\left(\frac{2K_H}{M_H}-\frac{2K_S}{M_S}\right)\Bigg/\left(\frac{1}{M_S t_S}+\frac{1}{M_H t_H}\right) \tag{15}$$

Also, (14) can be fulfilled by decreasing t_S to $t_{S\text{-}Critical}$, while keeping other film parameters constant

i.e. $$\left(H_{K-H}-\frac{J}{M_H t_H}\right)-\left(H_{K-S}+\frac{J}{M_S t_{S-Critical}}\right)=0$$

and then $$t_{S-Critical}=\frac{J/M_S}{\frac{2K_H t_H - J}{M_H}-\frac{2K_S}{M_S}} \qquad (16)$$

Parameters $J_{Critical}$ and $t_{S\text{-}Critical}$ are important for a bilayer system or a spring magnet. Substituting $J_{Critical}$ in (12) and (13), we find

$$H_{Critical}=\frac{2(K_S t_S + K_H t_H)}{(M_H t_H + M_S t_S)}=\frac{2K_{Eff}}{M_{Eff}} \qquad (17)$$

where $K_{Eff}=\dfrac{(K_S t_S + K_H t_H)}{(t_S + t_H)}$ and $M_{Eff}=\dfrac{(M_H t_H + M_S t_S)}{(t_S + t_H)}$ (18)

Equations (17) and (18) show that when the coupling constant reaches $J_{Critical}$, an exchange-coupled bilayer system can be regarded as a magnet with effective magnetization M_{Eff}, anisotropy K_{Eff} and thickness (t_S+t_H). If $J_{Critical}$ and $H_{Critical}$ as shown in (15) and (17) respectively, are substituted in the energy barrier equations (10) and (11), it can be obtained that

$$E_{B-S} = E_{B-H} = 0.$$

Consequently, both M_S and M_H are reversed at $H = H_{Critical}$ field and thus the “kink” disappears. Equation (15) indicates that the hysteresis loop will have no kinks when the coupling constant $J \geq J_{Critical}$, which decreases with the difference $(2K_H/M_H - 2K_S/M_S)$, and decrease in $M_S t_S$ or $M_H t_H$, where $2K_S/M_S$, $M_S t_S$, $2K_H/M_H$, and $M_H t_H$ are the coercivity and moment per unit area for soft and hard phases respectively. Equation (16) reveals that the critical soft-phase length is also related to the soft-phase properties and that the hysteresis loop has no kinks when the thickness of the soft phase is $t_S \leq t_{S\text{-}Critical}$, which has been confirmed by many experimental works. This conclusion is different from those derived from previous simulations [2]-[4].

D. *Maximum Energy Product $(BH)_{max}$*

The maximum energy product $(BH)_{\max}$ is the figure of merit characterizing the magnetic properties of a permanent magnet. Since $BH = (H+4\pi M_{eff}) \cdot H$ and $(BH)_{\max}$ is determined by $d(BH)/dH = 0$, $(BH)_{\max}$ can be expressed as

$$(BH)_{\max}=4\pi^2 M_{Eff}^{\;2}=4\pi^2\left(\frac{M_H t_H + M_S t_S}{t_H + t_S}\right)^2 \qquad (19)$$

if $H_{Critical} > 2\pi M_{Eff}$ or $\dfrac{2(K_S t_S + K_H t_H)}{M_S t_S + M_H t_H} > 2\pi\dfrac{M_S t_S + M_H t_H}{t_H + t_S}$

Equation (19) indicates the correlation between $(BH)_{\max}$ and the magnetic and structural properties of the hard-soft composites, which is useful for improving the maximum energy product $(BH)_{\max}$. This equation indicates that larger effective magnetization M_{Eff} may raise the $(BH)_{max}$ but will reduce $H_{Critical}$ as shown in (18). Therefore, a compromise value has to be chosen for M_{Eff}.

IV. Conclusion

The magnetic properties of an exchange-coupled bilayer system have been studied based on the energy barrier characteristics. A set of analytical solutions have been derived, which clearly indicate the correlation between the magnetic and structural properties of a hard-soft bilayer system. It has been revealed that the coercivities of soft and hard phases, H_{C-S} and H_{C-H}, are determined at the point at which the energy barriers vanish at $H = H_{C-S}$ or H_{C-H} respectively and the kink disappears when both energy barriers E_{B-S} and E_{B-H} vanish at $H = H_{Critical}$. A high $(BH)_{max}$ value can be obtained for a bilayer system which has a high effective magnetization M_{Eff} while retaining high $H_{Critical} > 2\pi M_{Eff}$. Contrary to the conclusions derived from previous simulations [2]-[4], this modeling analysis shows that the critical soft-phase $t_{S\text{-}Critical}$ is related not only to the hard phase but also to the soft phase properties. Although these conclusions are based on a rather simple model, they are valuable in understanding the magnetic and structural properties of an exchange-coupled nanocomposite magnet.

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[9] There may be some sign confusion , i.e. +H or –H, in Fig. 2 and (10)-(11), because Polar and Cartesian coordinates are used for energy (1)-(4) and *M*(*H*) loop in Fig. 2, respectively. For example in the Fig. 2, the field *H* in the second quadrant should be -(negative) in the Cartesian coordinate, however *H* is +(positive) with θ=180° in the Polar coordinate. In this paper, the “+” or “-” sign of the *H* field follows the rule of the polar coordinate.